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1. Introduction

The final AIPM project report consists of six sections. Each section includes information on the original AIPM project and extension work on the high temperature design. The *first section* ***(1)*** provides an overview of the program and highlights the significant targets to meet at the end of the program. The *next section* ***(2)*** summarizes the significant technical accomplishments by the SEMIKRON AIPM team during the course of the project. Greater technical details are provided in a collection of all the quarterly reports which can be found in the appendix. *Section three* ***(3)*** presents some the more significant technical data collected from technology demonstrators. *Section four* ***(4)*** analyzes the manufacturing cost or economic aspects of producing 100,000 units / yr. *Section five* ***(5)*** describes the commercialization efforts of the AIPM technology into the automotive market. The *last section* ***(6)*** recommends follow on work that will build on the efforts and achievements of the AIPM program.

2. Project Overview & Goals

The AIPM project began in January 2000 as a 3 year program to develop cost effective motor drives for the emerging EV/HEV market. This project can be divided into 3 phases (i) Design and verify a motor drive for the application that meets or exceeds the DoE set technical targets (ii) develop a plan to produce 100k units /yr at $7/kW and (iii) commercialize the product.

In April 2004, when the original AIPM program term was concluded, the technical target was revised and the program extended by 2 years to include a high temperature requirement (see summary of technical goals in Table 1).

Table 1 DoE technical targets for the AIPM.

Item No.	Parameter	DoE Goal	Achieved
1	Volume	12kW / liter	18.75 kW / liter
2	Continuous Power	30kW	120kW
3	Peak Power for 30 seconds	55kW	150 kW
4	Weight	5kW / kg	18.3 kW / kg
5	Peak Phase current	300 A pk	500 A pk
6	Max. coolant inlet temp	70ºC	70ºC
	Revised Max. coolant inlet temp	105ºC	n/a
7	DC battery voltage	200 to 450 VDC	200 to 450VDC
8	Efficiency	> 97%	97%
9	Life	15 yrs/150kmiles	15yrs/150kmiles

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3. Technical Achievements

All the technical targets set by DoE for the initial AIPM program has been met or exceeded (see Table 1). The project resulted in not just one module, but a range of modules to meet power levels up to 220kW. The modules successfully passed all the environmental and reliability tests listed in Table 2.

A breakthrough in Si device attachment was achieved to make it feasible to maintain reliability at higher temperatures. Along with other innovations, it can be concluded that high temperature AIPM is technically feasible. The impact on module economics is explained in a later section. Some of the major technical developments include:

- Continuous power rating that is 4 times greater than the program requirement.
- Peak power rating at least 2.7 times greater than requirement.
- Mechanical and vibration ratings tested to 1.8 times over the requirement.
- Significantly exceeds most the technical parameters set by DoE in the AIPM solicitation.
- Unique module packaging offers extremely low package parasitics, which negate the need for snubber capacitors.
- Use of a compact magneto resistive current sensor.
- SEMIKRON Sinter Technology of attaching Si devices to DBCs without solder results in a significant improvement in power cycling reliability of the present AIPM module.
- Bond coverage prolongs bond lift-off thus improving wire bond reliability
- High temperature 600V Trench gate IGBTs allow higher temperature operation, faster switching speed and higher current density.
- Various manufacturing process improvements to reduce cost.

Table 2 AIPM qualification tests successfully completed.

Test	Conditions	Acceptance criteria
High Temp Storage (HTS)	125º C for 1,000 Hrs	Must pass all functional test Refer Doc. No. 10-WI-015
Low Temp Storage (LTS)	-40º C for 1,000 Hrs	Must pass all functional test Refer Doc. No. 10-WI-015
Temperature cycle	-40º C to +125C for 100 cycles; 1 hr soak	Must pass all functional test Refer Doc. No. 10-WI-015
High Temp Reverse Bias (HTRB)	Vds = 60V, Vgs = 0V Tj= 105º C for 500 Hr	Igss/Iges < 200% of USL & Idss/Ices < 200% of USL & Rdson/Vcesat < 120% of initial

		value & 80% of LSL & Vgs/Vge < 120% of USL & Rthj < 120% of initial value & Visol remains unchanged
High Temp Gate Bias (HTGB)	Vds = 0V, Vgs = 20V Tj= 105º C for 500 Hrs	Igss/Iges < 200% of USL & Idss/Ices < 200% of USL & Rdson/Vcesat < 120% of initial value & 80% of LSL & Vgs/Vge < 120% of USL & Rthj < 120% of initial value & Visol remains unchanged
Power Cycle	Tj = 45º C to Tjmax = 125º C	>20k cycles for HV AIPM >15k cycles for LV AIPM
Humidity	RH = 85%, Ta=85º C for 1,000 Hrs	< 15% change in output phase current
EMI	100kHz to 18 GHz Rotate 90 deg. and repeat	TBD
Splash	water spray 0.25cm/min 45º Angle 5 minutes each side	< 15% change in output phase current
Salt Fog	5 parts salt, 95 parts water atomized Part 1: 24 hrs, part 2: 96 hrs	< 15% change in output phase current
Vibration	x, Breakpoint 5 Hz, Mag. .0055 G2/Hz y, Breakpoint 5 Hz, Mag. .0092 G2/Hz z, Breakpoint 5 Hz, Mag. .0965 G2/Hz x, Breakpoint 12 Hz, Mag. .20640 G2/Hz y, Breakpoint 8 Hz, Mag. .0760 G2/Hz z, Breakpoint 8 Hz, Mag. .0215 G2/Hz x, Breakpoint 100 Hz, Mag. .0500 G2/Hz y, Breakpoint 12 Hz, Mag. .0760 G2/Hz z, Breakpoint 14 Hz, Mag. .104 G2/Hz	< 15% change in output phase current & no visible damage
Drop	Lifted at one end to 45º angle and dropped on bench; Repeated on all four sides.	< 15% change in phase current & no visible damage
Shipping/packaging	122cm on to concrete backed plywood Unit packed in shipping container	< 15% change in output phase current & no visible damage
Shock	4, 14 Gpk half sine pulses 2, 22 Gpk Half sine pulses	< 15% change in output phase current & no visible damage

4. Technology demonstration

The AIPM design is based on the unique SEMIKRON pressure contact technology developed in the early 90s which eliminates the traditional copper base plate from power modules. It provides a more direct path for heat flow and improves module reliability in power cycling tests when compared to traditional base plate modules.

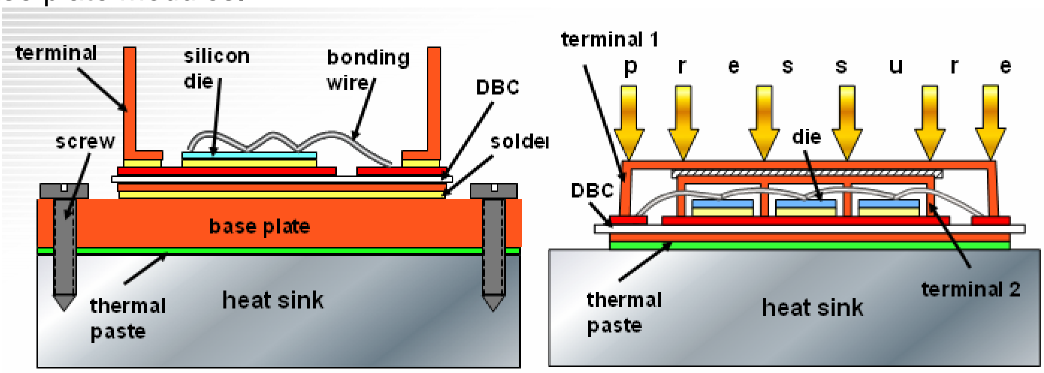


Figure 1 A traditional power module when compared to SK pressure contact system.

Since the pressure contact technology is applied to the heat sink interface, the other key areas of technology to be developed within the scope of the AIPM project includes, Si devices, bottom side die attach, top side die attach, current sensors and packaging materials.

High temperature Devices

For 105ºC coolant inlet, it is necessary that all the Si devices be rated at 175ºC. The project supported the development of new 600V trench gate IGBTs, CAL didoes, thin wafer technology (TWT) and Merged PIN Schottkey (MPS) diodes.

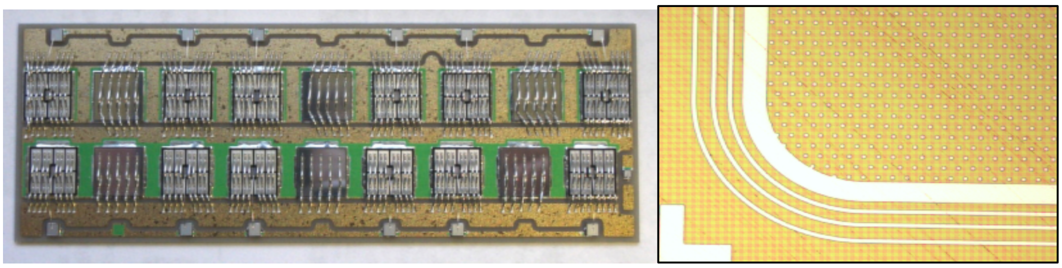


Figure 2 DCB with high temperature IGBT and diodes.

Bottom side die attach – Several concepts were evaluated, including over twenty (20) different types of lead free solder, five (5) types of epoxy or adhesive and sintering concepts. After comparing test data results it was decided that the sintering process offered the best solution for reliability as well as eliminated the need to find a lead free solder.

Data from testing samples of sinter attachment die and bond coverage shown in Figure 3 compares it against traditional soldered modules. The blue lines denote measure thermal resistance of soldered devices and the red line shown indicates the thermal resistance of the sintered devices. The data clearly shows the potential for sintered process with bond coverage to improve power cycling reliability by 4 to 5 times the traditional modules.

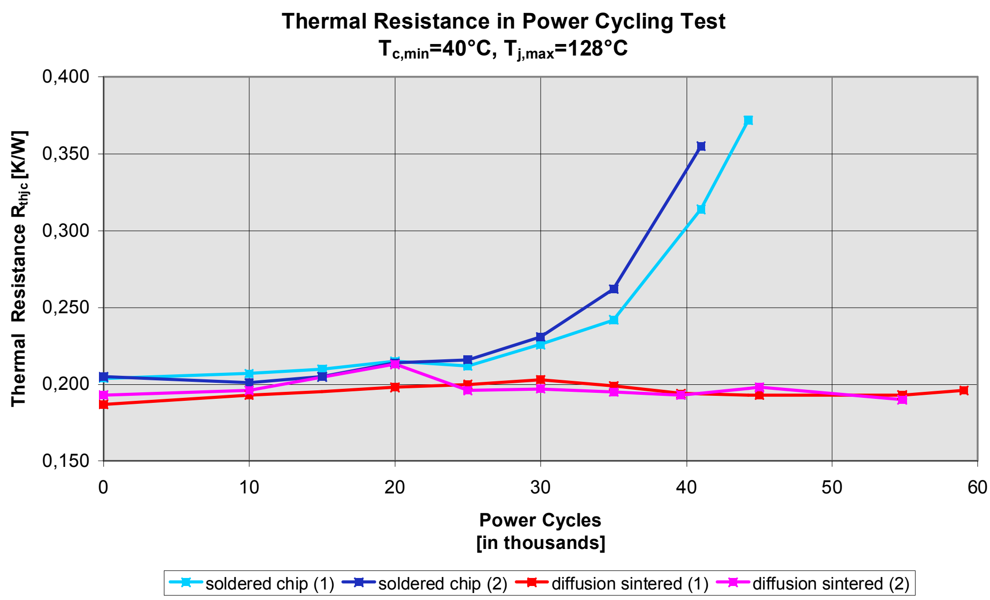
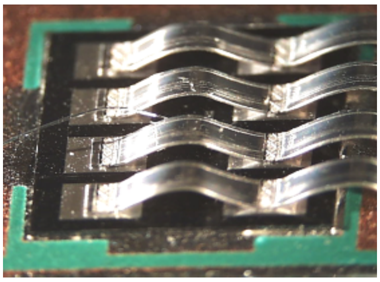


Figure 3 Improvement in power cycling reliability from sintering and bond coverage technology.

Top side die attach – Different bonding materials, various wire bond diameter and ribbon bond samples were tested to determine the optimum parameters of wire bonds for the high temperature silicon devices. After testing different samples to determine relationships between current density, wire bond diameter and reliability it is determined that the 300um wire Al bonds will be adequate.



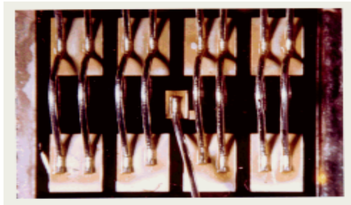


Figure 4 Ribbon bond test samples (left). Bondcoverage applied to the foot of each wire (right).

Bond coverage technology – An important observation was made after power cycling with chips which are partially coated with a polyimide layer. After removal of the polyimide (PI), the chip metallization under the PI-layer showed less damage due to reconstruction then the emitter pads, which were not covered. Therefore, polyimide was considered to be a promising candidate for lifetime improvements of Al bond wire contacts. Data shown in Figure 3 are from samples with polyamide drops applied to the bond wire base.

High temperature current sensors – Two basic sensing technologies, hall-effect and magneto resistive (MR) was considered for a low cost open loop current sensor to be included in the module. Both technologies were able to meet the cost targets in high volume but the MR sensors offered a compact size and better mounting features. For higher temperature operation (125ºC) both technologies have a viable solution and can meet the cost targets.

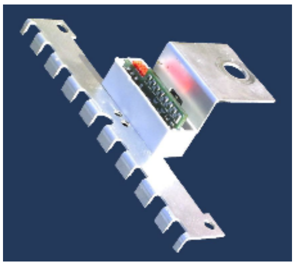


Figure 5 Magneto resistive current sensor integrated with the AIPM AC bus bar.

Packaging materials – The plastic packaging materials of the standard AIPM modules will have to be replaced with higher temperature plastics. Ultem 1000 was identified as the most technical and economically suitable solution. However, due to high cost of tooling plastic parts and the fact that the shape of the cover and housing could change before production it was decided not to tool the parts. The risk of not including the higher temperature plastics in the AIPM high temperature technology demonstrator is not considered high as the properties of the material is well understood.

AIPM Technology demonstrators – During the AIPM program two standard modules with thermocouple were delivered to ORNL for testing. After concluding the high temperature project an additional two units were delivered to demonstrate several high temperature technologies, including low temperature sintered die attachment, bond coverage, and high temperature Si devices. These demonstration modules are specially modified to include additional thermistors for collecting thermal data. The only major sub-components not included in the demonstrators are the DC link capacitors and the higher temperature plastics. The capacitors were not included in the SOW for the project extension. Since DoE will funding capacitor develop separately it made sense and Semikron not pursue its development with AIPM funding. The plastics were not tooled entirely for economic reasons, as the tooling costs are very high and chances are great that the shape of the plastics parts will change.

Figure 6 AIPM high temperature technology demonstrator.

5. Manufacturing & business economics

In addition to meeting the cost target of $7/kW, one of the stated goals was to have a plan in place to be able to produce 100,000 units / year at the end of the AIPM program. Currently Semikron has in place a dedicated AIPM manufacturing line in Hudson, NH for manufacturing 8,000 units / year. Should demand require it, this line can be expanded to accommodate 44,000 units / yr before having to invest in a new parallel manufacturing line.

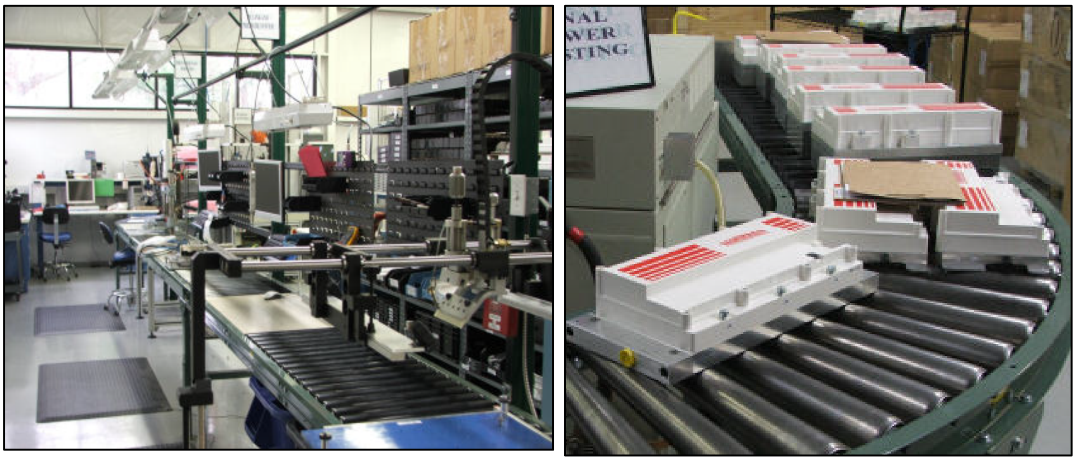


Figure 7 AIPM Assembly line at SEMIKRON in Hudson, NH.

The AIPM program has been highly successful in meeting the cost targets of the finished module (see Table 3).

Table 3 AIPM cost versus quantity

Volume (thousands)	0.1	1	100
Price ($ / kW)	18.6	12	6.6
DoE target ($/kW)	n/a	n/a	7

A cost break down of the standard AIPM shows the significant sub-components that make up the cost of the module. The impact of cost on the major sub-components for the higher temperature version of the AIPM is shown below in Figure 9. The capacitor remains the only major sub-component with a significant increase in price. As mentioned in the last section of the follow up work, there are two leading technologies for developing high temperature capacitors that may at some point become economical – Multi layer ceramic and polycarbonate based film technology. At present, the MLC appear to be able to meet the technical challenge but is about 2 times higher in cost at automotive quantities than we would like it to be. Additionally, there is also concern about its failure mode. The film capacitor offers the right price but for the same amount of capacitance in the standard AIPM module (1 mF) it will be approximately 3 times bigger in size.

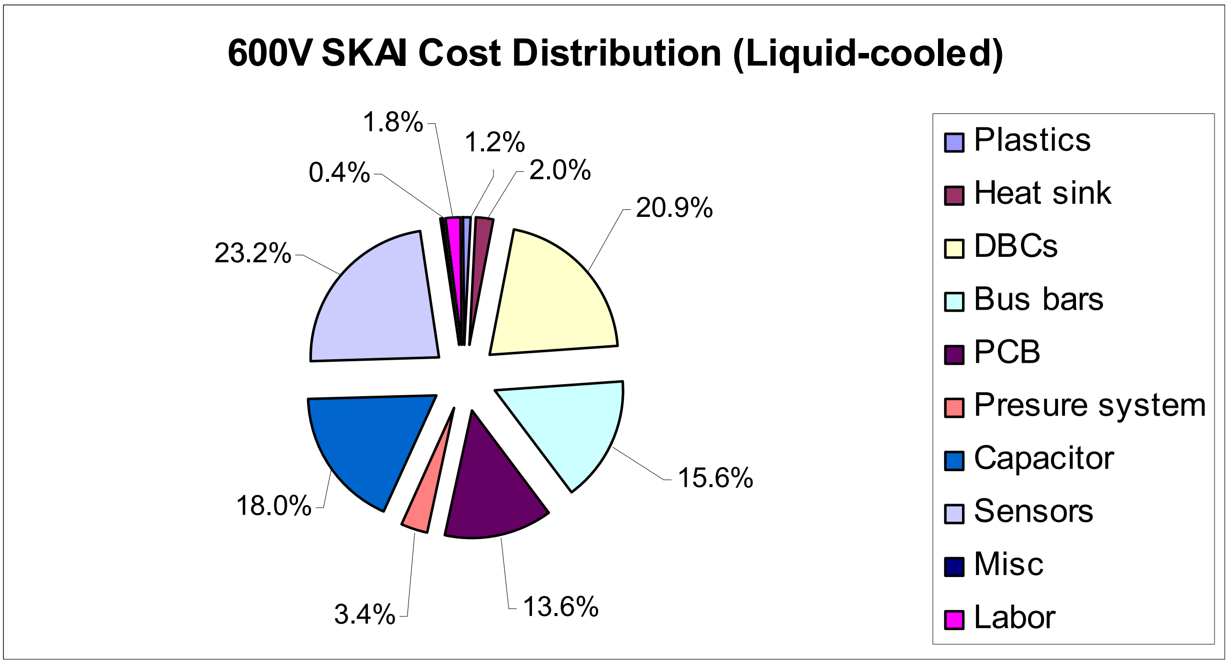


Figure 8 standard AIPM cost breakdown at lower quantities.

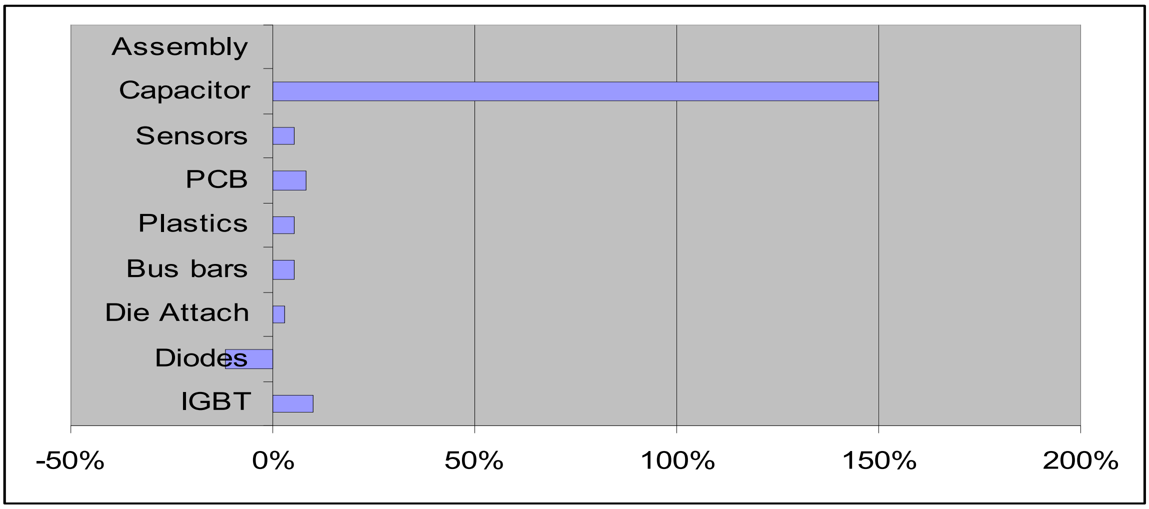


Figure 9 Percent increase/decrease in sub component cost for high temperature AIPM.

6. Commercialization

The technology developed under the AIPM program was introduced to the market under the product line name - SKAI (**S**emi**K**ron **A**dvanced **I**ntegration). Two distinct groups of products make up the SKAI product line – Low Voltage (LV) and High Voltage (HV) SKAI. The classification is based on the technology and voltage rating of the switching devices used in the module. LV SKAI modules use trench MOSFET devices (75V, 100V & 150V) and the HV SKAI products use IGBT devices (600V & 1200V). See figure below for the complete list of SKAI products currently offered for sale. A comprehensive marketing plan is in place to the modules to be sold into the automotive, off highway vehicle and material handling vehicle markets.

Figure 10 commercially offered SKAI models

In 2004, delivery of 600V SKAI products to GM's alternative energy vehicle program helped Semikron secure the supplier of the year award from GM. Last year Semikron International was also selected by IEEE-Spectrum magazine as the top company in power electronics for the next decade.

The primary target market for the product remains the automotive industry for which the product was originally developed, with strong interest from material handling vehicle manufacturers, mining vehicles, distributed generation and the locomotive industry. Use of SKAI products usually translates to shorter time to market and that makes these products an attractive sell to specialty drives manufacturers operating in certain niche market segments. The table 2 below summarizes some of the key market segments in which SKAI products have been designed into.

Figure 11 AIPM based SKAI products are being heavily marketed to the automotive industry.

Table 4 SKAI applications by market segments.

No.	Industry	Application	SKAI model
1	Automotive	Hybrid or fuel cell vehicle traction drive	4001 GD06 series
2	Mining	Hydraulic pump motor drive	360 MD20[1] series
3	Mining	Vehicle traction motor drive	3001 GD12[2] series
4	Transportation	Aux. Inverter / compressor drive	3001 GD12[2] series
5	Others	Traction motor drives Aux. inverters HVAC systems	6001 MD10 series 3001 GD12 series 7001 MD075 series

[1]New 200V MOSFET model under development.
[2]See Appendix for further details.

7. Follow on work

Follow up work will be to integrate the various high temperature technologies developed into a new motor drive design that will emphasize higher temperature operation, manufacturability and cost. The key areas of development will be:

a. **Reliability** – Module reliability can be greatly improved further if it is possible to eliminate the use of wire bonds altogether.

b. **Capacitor** - Two capacitor technologies were also identified as potential candidates for the high temperature application – Multi Layer Ceramics (MLC) and polycarbonate based film. Prototypes of these capacitors should be developed for testing in working high temperature AIPMs.

c. **Module Integration** – The MLC offers an opportunity to further shrink the module size.

d. **Connectors** – New and improved connector technology should be developed to better seal the module against environmental elements, reduce cost and standardize.

8. Acknowledgements

SEMIKRON wishes to thank Susan Rogers at DoE and Steve Cooke at NETL for their support of this program. Laura Marlino and her team at ORNL for performing the necessary lab testing on sample AIPM modules to validate performance. We also thank the EE tech team for their valuable input and guidance.

APPENDIX

Quarterly Reports
January 2000 to June 2006